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## Disclaimer



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# A High Efficiency Grazing Incidence Pumped X-ray Laser

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## Abstract

The main objective of the project is to demonstrate a proof-of-principle, new type of high efficiency, short wavelength x-ray laser source that will operate at unprecedented high repetition rates (10Hz) that could be scaled to 1kHz or higher. The development of a high average power, tabletop x-ray laser would serve to complement the wavelength range of 3rd and future 4th generation light sources, e.g. the LCLS, being developed by DOE-Basic Energy Sciences. The latter are large, expensive, central, synchrotron-based facilities while the tabletop x-ray laser is compact, high-power laser-driven, and relatively inexpensive. The demonstration of such a unique, ultra-fast source would allow us to attract funding from DOE-BES, NSF and other agencies to pursue probing of diverse materials undergoing ultra-fast changes. Secondly, this capability would have a profound impact on the semiconductor industry since a coherent x-ray laser source would be ideal for "at wavelength" ~13 nm metrology and microscopy of optics and masks used in EUV lithography. The project has major technical challenges. We will perform grazing-incidence pumped laser-plasma experiments in flat or groove targets which are required to improve the pumping efficiency by ten times. Plasma density characterization using our existing unique picosecond x-ray laser interferometry of laser-irradiated targets is necessary. Simulations of optical laser propagation as well as x-ray laser production and propagation through freely expanding and confined plasma geometries are essential. The research would be conducted using the Physics Directorate Callisto and COMET high power lasers. At the end of the project, we expect to have a high-efficiency x-ray laser scheme operating below 20 nm at 10Hz with a pulse duration of ~ 2 ps. This will represent the state-of-the-art in x-ray lasers and would be a major step forward from our present picosecond laser-driven x-ray lasers. There is an added bonus of creating the shortest wavelength laboratory x-ray laser, below 4.5 nm and operating in the water window, by using the high-energy capability of the Titan laser.

## 1. Introduction and Motivation

Until fairly recently, x-ray lasers have been generated by large, high-power lasers with a single-shot, low repetition rate capability. The first laboratory x-ray laser demonstration used the Novette laser with 2 kJ, 527 nm single 450 ps laser pulse to generate a ~20 nm Ne-like Se ion laser [1]. A number of new applications e.g. "water-window" microscopy of biological cells [2], soft x-ray interferometry [3] and radiography [4] of dense laser-produced plasmas followed from the x-ray laser source development. However, the size of the laser driver and the low repetition rate, several shots/day, made the experiments expensive and limited the ability to deliver extensive data sets. Subsequently, a variety of techniques using multiple pulses [5] or transient excitation using short ps laser pulses [6] were introduced to reduce the pump energy required down to ~150 J to less than 10 J, respectively. These techniques improved a number of important laser-produced plasma characteristics essential for x-ray laser generation. The lower laser driver energy then allowed the use of tabletop drivers, e.g. the LLNL Compact Multipulse Terawatt (COMET) laser, and gave improvement in shot rates to 1 shot/4 minutes and typically 50 – 100 shots/day [7]. This was still far from the real benefits of high average power x-ray sources operating at 1 Hz or higher. The activities in this area can be summarized by the timeline graph below shown in Figure 1. Laser pump energy and repetition rate are shown from the start of the laboratory x-ray laser activities in 1984 to 2005. Included are some of the recent tabletop facilities operating at longer wavelengths.

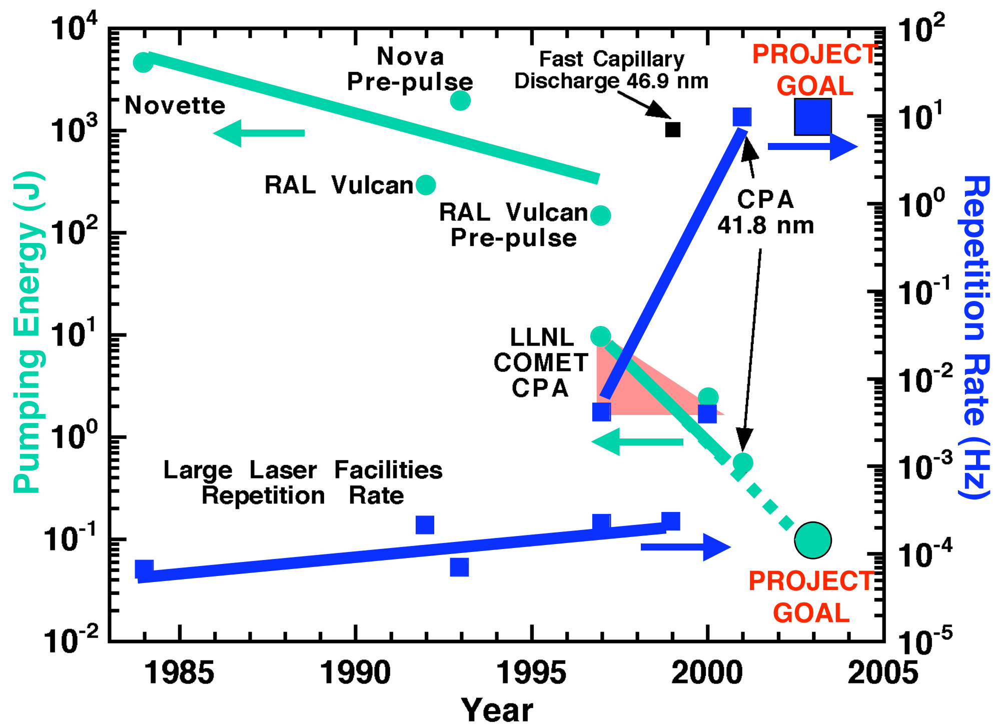


Fig. 1 Time line of optical laser pump energy (green round symbols) and repetition rate (blue square symbols) used to drive x-ray lasers over the last two decades. Solid lines are included to guide the eye through the data points. The project goal achieved a sub-20 nm x-ray laser for this Laboratory Wide research is shown at 150 mJ and 10 Hz.

The major goal of this project was to look at ways of improving the efficiency of generating the x-ray laser. If the laser pump energy could be reduced then a high repetition soft x-ray source could be generated at LLNL. A specific objective was to conduct the research on the existing small Jupiter laser facilities that had a high repetition rate of 10 Hz but were limited to energy below 200 mJ/pulse. The major theme of this project was based around a novel idea proposed by Dr. Shlyaptsev [8 - 11]. The laser absorption of the pump laser could be enhanced in the x-ray laser gain region by actively using refraction of the pump laser at a grazing incidence angle to the target to improve the coupling efficiency. Hence the name Grazing Incidence Pumping (GRIP) was chosen to illustrate the fact that the incident pump laser beam angles were typically less than 25° where most x-ray laser schemes to date were pumped either at 90° (at normal incidence to the target) or less commonly close to 0° (longitudinal pumping).

In the 3 years of the project we were able to demonstrate this x-ray lasing technique by reducing the required pump energy by more than an order of magnitude from our previous research [7] to 150 mJ/pulse at 10 Hz [11, 12]. This was achieved for the desired goal of a sub-20 nm x-ray laser. We are now at the point where 150 mJ – 1 J energy/pulse, 5 – 10 Hz, short pulse laser pumps can generate a 10 – 35 nm x-ray lasers. Some of these x-ray lasers now operate in the saturation regime with output energy approaching ~1 µJ/pulse and a few µW average power down to wavelengths ~13 nm [13, 14]. This type of x-ray laser source has been quickly adopted by many groups around the world [15] and can be used to extend both the higher average power x-ray source characteristics as well as the shorter wavelength capability using a larger laser driver. These future possibilities are outlined briefly in the section at the end of this Final Report titled *Collaborations*.

This report is split into sections that describe the *Grazing Incidence Pumping Method*, *Experimental Achievements*, *Summary*, *Acknowledgements*, *References*, *LDRD and External Funding*, *Collaborations*, *Publication List*, *Invited Talks List* and *Conference Presentations*.

## 2. Grazing Incidence Pumping Method

A brief introduction to the main pumping geometries is necessary to place the significance of the GRIP scheme into perspective. The major development over the last 10 – 12 years has been the use of two laser pulses, one of which is a picosecond duration pulse, to generate the x-ray laser [6]. Typically a long ~ 1 ns pulse is focused at normal incidence to the target in a line focus to generate a plasma. The objective of the first pulse is to setup the x-ray laser gain medium with the plasma close to the Ne-like or Ni-like ionization stage. A short delay allows the density profile to relax which helps in the propagation and amplification of the x-ray laser through the gain region. The short picosecond pulse also at normal incidence is then fired into the pre-formed plasma. This second pulse focused in a line at an irradiance of $10^{14}$ – $10^{15}$ Wcm$^{-2}$ rapidly raises the electron temperature to 500 – 1000 eV and collisionally pumps the upper state of the x-ray laser. The main lasing is on a 3p – 3s transition for the Ne-like ion schemes or the 4d – 4p transition for the Ni-like ion scheme. The lasing takes place by amplified spontaneous emission along the plasma column length and is single-pass. Since the duration of the gain lasts for picoseconds a traveling wave irradiation geometry is required for the ~1 cm long plasma column. This technique, called normal incidence or transverse pumping, for picosecond-driven collisional schemes has been very successful and implemented in different laboratories.

A second geometry called longitudinal pumping, requires the optical pump beam to be focused at high irradiance into the end of the plasma column, is attractive since it allows efficient traveling-wave pumping and therefore co-propagation with the x-ray laser pulse. Saturated outputs have been produced from Optical Field Ionized (OFI) pumped x-ray lasers, Pd-like Xe at 41.8 nm [16] and Ni-like Kr at 32.8 nm [17] have been demonstrated. These lasers were pumped with energy < 1 J in ~40 fs and a repetition rate of 10 Hz as shown in Fig. 1. A longitudinal pumped Ni-like Mo x-ray laser at 18.9 nm has also been demonstrated [18] where a 300 ps pre-pulse was incident normal to the target creating a preplasma which was then pumped by a short pulse from the longitudinal direction. This laser operated with total pump energy of 150 mJ and produced a highly directional output but was not saturated. Figure 1 also shows an x-ray laser not pumped with an optical laser, the table-top capillary discharge laser operating at 46.9 nm, which has produced millijoule level laser pulses at a repetition rate of several Hz [19].

The transverse and longitudinal pumping have disadvantages that affect the efficiency and ability to scale to shorter x-ray wavelengths. In the transverse case most of the pump energy is absorbed near the critical surface at $10^{21}$ cm$^{-3}$, for 1054 nm wavelength, and not in the active gain region at $10^{20}$ cm$^{-3}$ electron density required for many of the mid-Z x-ray lasers. In this higher density region high density gradients exists and refraction limits propagation of the x-ray laser. Therefore, low laser absorption and coupling efficiency into the plasma region of interest is one of the main issues for transverse pumping. Longitudinal pumped lasers have potentially higher efficiency but have other limitations. These are mainly in areas of absorption, refraction, and relativistic self-focusing of the high intensity short pulse optical pump through the plasma. This reduces the plasma column length and requires a lower density regime in order to successfully propagate the pump pulse through the plasma medium. While this geometry has been demonstrated and works well for the OFI lasers mentioned above, the lower plasma column density limits the x-ray laser to longer wavelengths above the 20 nm region of interest for this work.

The GRIP pumping scheme as shown in Fig. 2 uses a long prepulse and a short pumping pulse, as in the usual transverse schemes, but with a factor of 20× less energy for other picosecond-driven collisional x-ray lasers [7]. In this case a 200 ps pre-pulse is incident on the target in a line focus creating a pre-formed plasma with a tailored density profile. After a certain delay, chosen to optimize this density profile, the short pulse is incident on the target, also in a line focus, but at a grazing incidence. The refraction is used in the GRIP scheme to optimally couple the optical drive beam. The absorption in the plasma corona is increasing as $1/\sin(\phi)$ of the grazing angle $\phi$ and refraction gradually turns the rays $\phi$ towards 0° and parallel to the target. Then the absorption efficiency is dramatically increased up to the turning point, where the plasma is pumped longitudinally. The turning point is at the maximum density position of the gain region. The short pulse is then refracted back into the gain region where there is

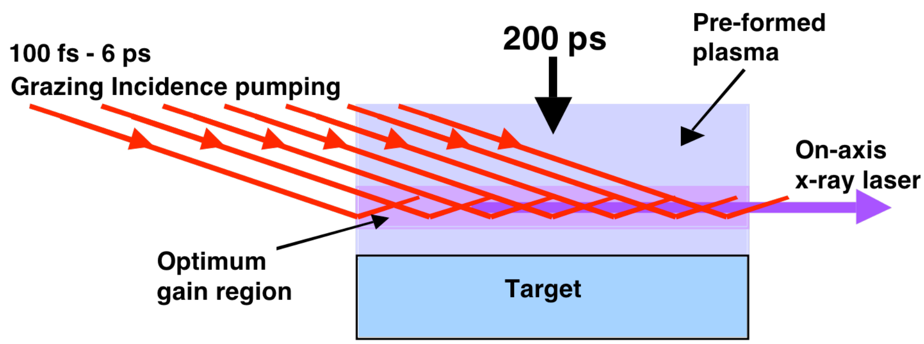


Fig. 2 Schematic of grazing incidence pumping (GRIP) scheme. A pre-formed plasma is first produced on a flat target to generate the optimum gain region. GRIP geometry uses short pulse of 100 fs - 6 ps duration, 800 nm wavelength laser to strongly heat this region producing efficient on-axis x-ray lasing at a pre-determined density.

additional absorption as the beam exits the plasma. The refraction also works to direct the pumping power precisely into the gain region because all rays with a given initial angle will pass through the same density at the turning point and independent of density gradients or the profile. Therefore, the short pulse beam traverses the density region of interest being simultaneously strongly absorbed and refracted. This refraction benefits the pumping as the angle of incidence is chosen for a given electron density in order to maximize the deposition of laser energy within the optimal gain region. The traveling wave is inherent in this scheme and each section of the short pulse line focus pumps a new section of target as for the transverse pumping case. This means that the laser energy is brought in from the side and that there is no physical limit to the amount of laser energy used (as in the longitudinal pumping scheme) or length of the plasma line focus being heated. The x-ray laser beam propagates along the axis of the plasma column and is strongly amplified. The important point is that the grazing angle selectively pumps the x-ray laser gain region over any other region of the plasma. The choice of the grazing incidence angle is dependent on the laser pump wavelength and the electron density where the given x-ray laser is predicted to operate.

To illustrate this we show the conditions for the Ni-like Mo 4d – 4p x-ray laser at 18.9 nm. RADEX simulations were run and predicted the optimum pump conditions for the Callisto 800 nm laser running at 10 Hz [9]. The density at the turning point is optimized for a particular x-ray laser from atomic kinetics models and refraction of the x-ray signal itself. Given this selected density and the wavelength of pumping laser the angle of incidence is chosen. For a maximum density within the gain region $n_{e0}$ and the critical density $n_{ec}$ for the optical pump beam the required angle of incidence is obtained from a simplified version of the refraction formula $\phi_r = \sqrt{n_{e0}/n_{ec}}$ [20]. With a maximum density of $n_{e0} = 1\text{x}10^{20}$ cm$^{-3}$ for the gain region and the critical density for the 800 nm optical pump of $n_{ec} = 1.74\text{x}10^{21}$ cm$^{-3}$ the chosen angle of incidence is $\phi_r = 13.7^o$. This angle is measured relative to the x-ray laser media axis, not relative to the normal, in the same way the deflection angle of the x-ray laser due to refraction is measured.

Figure 3 shows RADEX modeling carried out for the Ni-like Mo x-ray laser at 18.9 nm. The Callisto 10 Hz laser has a maximum of 250 – 300 mJ energy available before compression: This dictated a short line focus with a narrow width and less than 100 mJ in each beam for the experimental conditions. The long pulse, 200 ps in duration, is incident normal to the target with 75 - 120 mJ total energy giving an intensity of $1.5\text{x}10^{11}$ W/cm$^2$. The short pulse, 4 ps in duration, with 64 - 100 mJ total energy gives an on target intensity of $5\text{x}10^{12}$ W/cm$^2$. The long pulse creates the preformed plasma with particular electron density gradients. At $\Delta t = 500$ ps after the peak of the long pulse an optimum electron density profile is created with electron densities of 0.5 - $1\text{x}10^{20}$ cm$^{-3}$ in the gain region, Fig. 3 (a). The gain region exists 15 - 30 μm from the target and is shown as the shaded area. Shallow density gradients are present here, which improve the propagation of the x-ray laser beam along the plasma column. The short pulse is incident at this time resulting in an increase in the electron temperature. Two cases for different angle of incidence are presented: $14^o$ grazing incidence angle to the target (solid line) and normal incidence (dashed line) are compared with the same pump energy. The GRIP case has the higher electron temperature. More importantly, the maximum temperature is achieved in the density region of interest immediately below $10^{20}$ $cm^{-3}$. Figure 3 (c) shows that the laser energy is absorbed within the gain region for grazing incidence pumping compared to at critical density, $n_{ec} = 1.74 \times 10^{21}$ $cm^{-3}$, for normal incidence. This is in agreement with the temperature plot of Fig. 3(b). This increase in absorption, from 5-8% in the case of normal incidence to potentially as high as 50% for grazing incidence, corresponds to an improvement in efficiency where a saturated x-ray laser may be pumped with an optical laser of reduced pump power and at an increased repetition rate. The simulations show a dramatic improvement in the plasma conditions using the GRIP geometry.

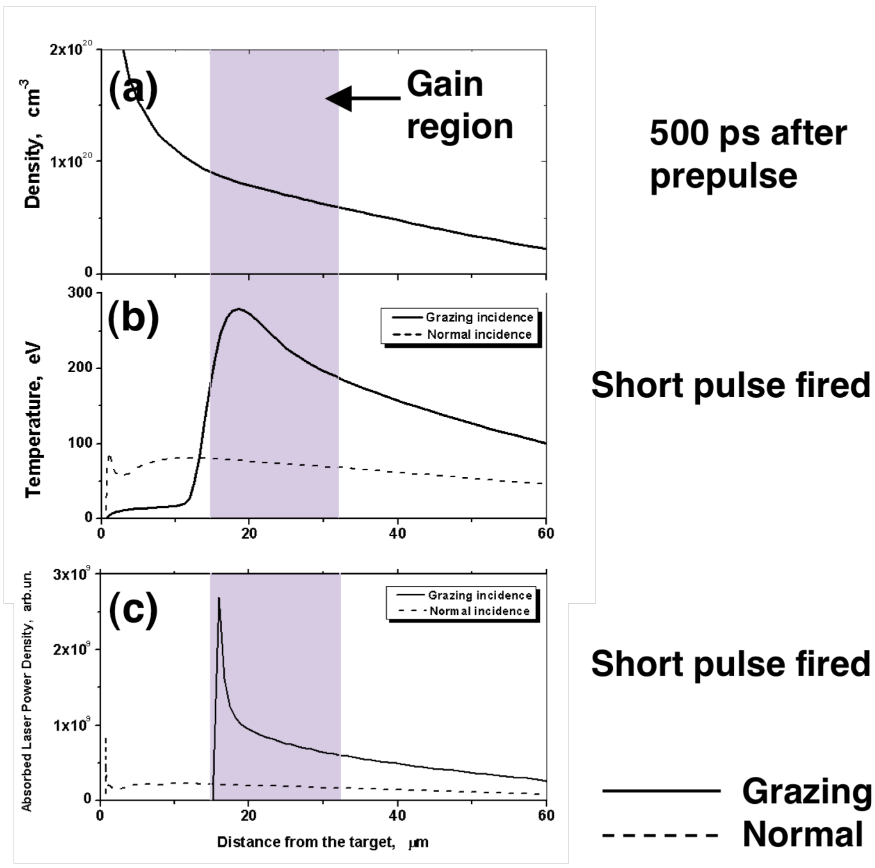


Fig.3 RADEX simulations show (a) electron density profile of x-ray laser medium for Ni-like Mo preformed plasma, (b) electron temperature and (c) absorbed laser energy of short pulse for normal incidence (dashed line) and grazing incidence (solid line) pumping.

## 3. Experimental Achievements

Several experimental campaigns were conducted to demonstrate the GRIP scheme on the Callisto and COMET lasers. Additional supporting experiments using x-ray laser interferometry to characterize the density profile of the gain medium for various candidate x-ray lasers were performed. The results from these are described below.

### 3.1 X-ray Interferometry Characterization Experiments

These experiments were conducted in collaboration with the Colorado State University group of Prof. Jorge Rocca with the participation of his student Jorge Filevich. The methodology for the x-ray laser interferometry can be found in further detail [11. 21 – 23]. Two specific campaigns were conducted at LLNL using the picosecond 14.7 nm x-ray laser interferometer to probe short plasma columns of laser heated Mo and Pd targets. These were two of the materials studied using the GRIP technique. In general the density profile produced by the pre-pulse laser at normal incidence was relevant for understanding both the GRIP scheme as well as the transverse pumping scheme. This is important for several reasons: The pre-pulse conditions are important for setting up the gain medium for generation of the x-ray laser when the short pulse arrives regardless of the pumping geometry used. Secondly, the x-ray laser

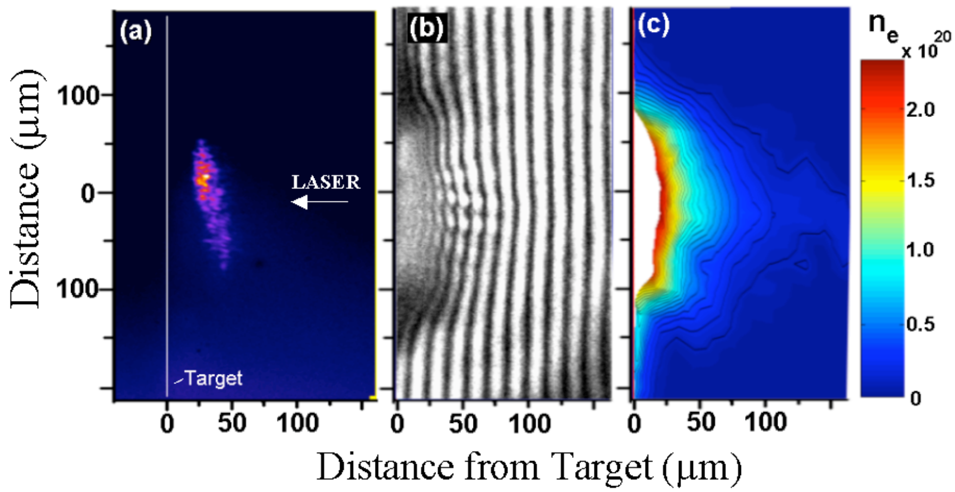


Fig.4 (a) Ni-like Pd 14.7 nm x-ray laser gain region measured by near-field imaging technique and (b) corresponding x-ray laser interferogram and (c) 2-D density profile under same conditions.

interferometry technique uses the Pd x-ray laser pumped by the transverse geometry. This transverse geometry has been the workhorse of all of our x-ray laser activities and applications to date.

Figure 4 shows a result for an experiment that combined the near-field x-ray imaging technique of the x-ray laser exit pattern and 2-dimensional density profiles of the pre-formed plasma using x-ray laser interferometry [21]. The near-field image in Fig. 4(a) indicates the position where the x-ray laser exits the gain region relative to the target surface with the two laser pulses (long and short pulse). The interferogram, Fig. 4(b), is taken of the preformed plasma with the long pulse only under similar conditions to Fig. 4(a). This gives a snapshot of the density profile at the time when the short pulse arrives. Figure 4(c) is the density profile. Comparison between the data from the two techniques gives the position where the gain region is producing the best amplification at ~$2 \times 10^{20}$ $cm^{-3}$. Pulse duration of the short pulse as well as the delay between the two pulses was changed as part of the detailed study [21]. There are some additional details not covered in this report to extract the final results: These include the ray-tracing of the Pd x-ray laser line through the above density profile, as well estimates of the refractive index correction due to the plasma Pd bound electrons and small changes in the ionization due to heating by the short pulse. This work was a milestone for the picosecond-driven transverse pumping scheme and gave us better insight into the dynamics of the x-ray laser generation.

### 3.2 10 Hz Ni-like Mo 18.9 nm GRIP Experiments

The experiment to produce a 10 Hz, Ni-like Mo 18.9 nm x-ray laser, Fig. 5, was conducted on the 800 nm wavelength Callisto (JANUSP) laser at LLNL. A chamber and focusing optics were designed specifically for this experiment. The grazing incidence angle was chosen to be 14° to pump the turning point electron density of $10^{20}$ $cm^{-3}$. An on-axis parabola with focal length of 91 cm was inclined at an angle of 7° to the short pulse beam to produce a short line focus of 25 - 30 μm (FWHM) × 0.4 cm long on

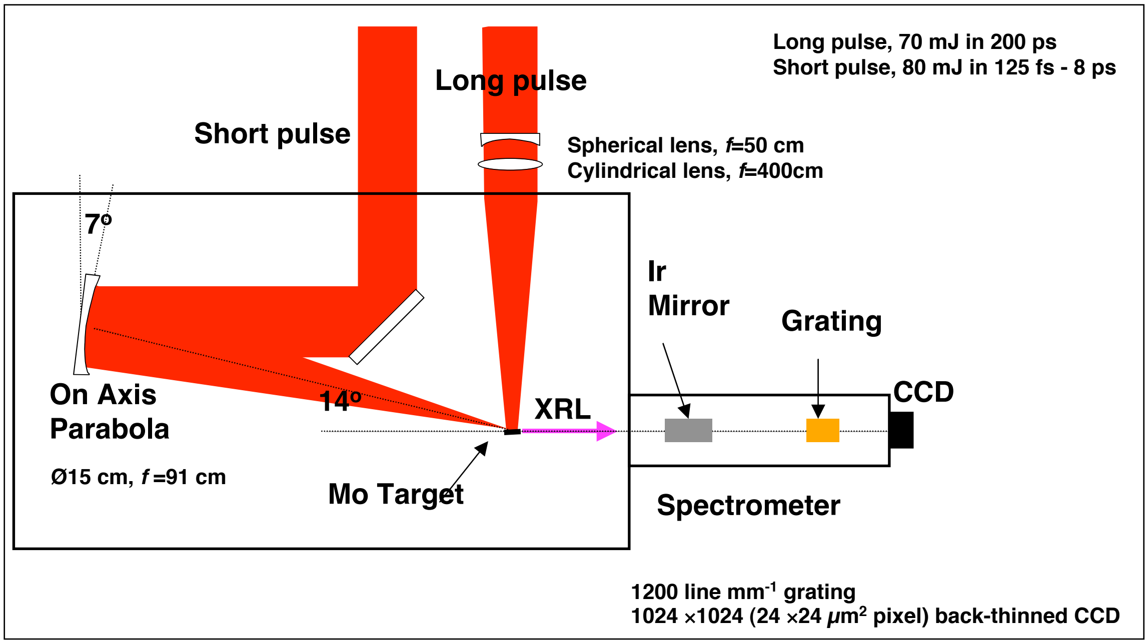


Fig. 5 Target chamber layout for generating x-ray laser using grazing incidence pumping geometry. Pre-pulse beam irradiates laser solid target at normal incidence while main (or short) pulse is incident at a specified grazing incidence. Grazing angle for short pulse is shown for 14°.

a flat, polished Mo slab. The pulse duration could be varied from 125 fs to 8 ps and the maximum laser energy delivered on target was ~80 mJ. The long 200 ps pulse was focused to a line 0.5 cm in length using a combination of a spherical lens, $f$ = 50 cm, and a cylindrical lens, $f$ = 400 cm. The maximum energy available in this beam was ~60 - 70 mJ. The best lasing results for this experiment were achieved when a narrow line focus of ~15 µm (FWHM) was produced, corresponding to an irradiance of $5 \times 10^{11}$ W cm$^{-2}$. Slab targets of various lengths from 0.1 cm up to 0.4 cm were irradiated with the two overlapped beams. The optimum x-ray laser output was observed when the delay between the two laser beams was set to 500 ps [12]. The 18.9 nm $4d - 4p$ laser line was observed to be emitted with a deflection angle of ~ 3.5 mrad away from the target and was observed with an on-axis 1200 line mm$^{-1}$ grating spectrometer with a thermoelectrically cooled back-illuminated charge-coupled device (CCD) 1024 × 1024 (24 µm × 24 µm pixel) detector. Various thicknesses of aluminum foils from 0.2 – 2 µm were placed in front of the spectrometer to attenuate the x-ray laser signal. In addition multilayer mirror optics were used to image the near-field pattern of the x-ray laser.

We summarize the results of this experiment using a total energy of 150 mJ focused onto the target. When the conditions were optimized as described above the x-ray laser could be observed for different short pulse durations though the shortest and longest pulses had relatively low output. The best lasing output was observed with a pulse duration of 1.5 ps corresponding to an irradiance of $5 \times 10^{13}$ W cm$^{-2}$ and a delay of 500 ps between the two pulses. The x-ray laser was observed to disappear when the laser energy in both beams was lowered by ~10 – 15%. This indicated that the laser pump conditions were just above the threshold for lasing. Figure 6 (a) and (b) show a typical intensity lineout and horizontal beam directional pattern for a single-shot spectrum from a 0.4 cm slab target. In spite of the narrow line foci used in the experiment the x-ray laser exhibits a very uniform and symmetrical beam pattern with a small deflection angle away from the target. This is consistent with good propagation and amplification within the ~$5 \times 10^{19}$ cm$^{-3}$ density region. The intensity versus length plot is displayed in Fig. 6 (c). The small signal gain is determined to be 55 cm$^{-1}$ for 0.2 cm with a slow roll-off at longer targets. The overall GL product was estimated to be 14 and close to saturation [12].

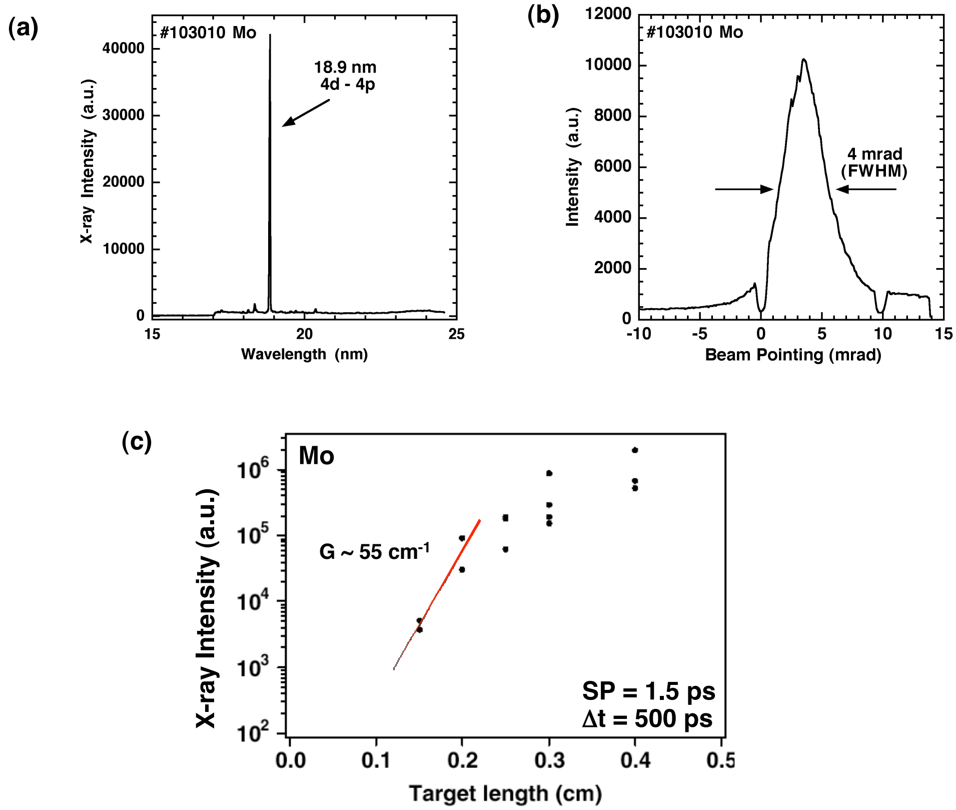


Fig. 6 (a) Typical spectrum from an irradiated 0.4 cm Mo slab target showing strong emission from the 18.9 nm Ni-like Mo laser line. (b) A lineout through the same shot indicating the horizontal beam pointing characteristics of the 18.9 nm x-ray laser. Beam deflection angle and divergence is 3.5 mrad and 4 mrad (FWHM), respectively. (c) Intensity vs length scan for Mo slab targets irradiated with 70 mJ, 200 ps pulse followed by 1.5 ps grazing incidence pumping beam. Time delay of $\Delta t = 500$ ps between the two pulses gives highest x-ray laser output. Small signal gain is determined to be 55 $cm^{-1}$.

### 3.3 Ni-like Pd 14.7 nm GRIP Experiments Using 2ω Drive Beams on COMET

The experiments were repeated on the Compact Multipulse Terawatt (COMET) laser using the fundamental 1054 nm wavelength beam as well as the frequency doubled light for the short pulse. The main goal was to apply more energy required to study the generation of shorter wavelength x-ray lasers. A further consideration was to increase the laser focus size to heat a larger gain volume. A final point was to investigate the x-ray laser parameters at different laser wavelengths 527 nm, 1054 nm and grazing incidence angles 10°, 13° and 20° for the short pulse. We briefly report a few results for 10° grazing incidence for 527 nm laser wavelength corresponding to a turning point at $\sim 1.2 \times 10^{20}$ $cm^{-3}$ density and will comment in detail in future publications. The COMET laser was set up to use the 600 ps, 1054 nm laser with 1.2 – 1.5 J energy focused into a 40 μm (FWHM) × 8 mm line focus at normal incidence. A 1.5 ps short pulse beam was frequency doubled to 527 nm with ~1.3 J energy in a 40 μm (FWHM) × 7 mm line focus. We investigated targets of Mo, Pd, Ag and Sn but concentrated mainly on the higher Z materials. Our initial expectation was that a four times increase in laser energy e.g. 0.6 – 1 J total energy should be sufficient to pump these longer targets. However pumping energies above 2 J were required. Nonetheless very strong lasing was achieved on the Ag and Pd $4d - 4p$ lines at 13.9 nm and 14.7 nm, respectively. The laser drive fluences on target are similar to the results reported by the Colorado group [24]. The optimum delay before firing the short pulse was found to be 200 ps relative to the peak of the long pulse. Figure 7(a) shows a spectrum for a 0.6 cm Pd target. The x-ray laser is driven into the saturation regime and requires to be filtered with 200 nm of aluminum to prevent the CCD from saturating. Figure 7(b) is an intensity versus length scan for the Pd x-ray laser showing strong exponentiation up to 0.3 cm targets with a small signal gain estimated to be ~45 $cm^{-1}$. The x-ray laser goes into saturation in a predictable manner. Silver targets show similarly strong output as the Pd while the Sn line although lasing is considerably lower in intensity, Fig. 7(c). Note that each spectrum in Fig. 7(c) has been filtered slightly differently: Pd with 200 nm Al, Ag with 200 nm Lexan/75 nm Al, Sn with

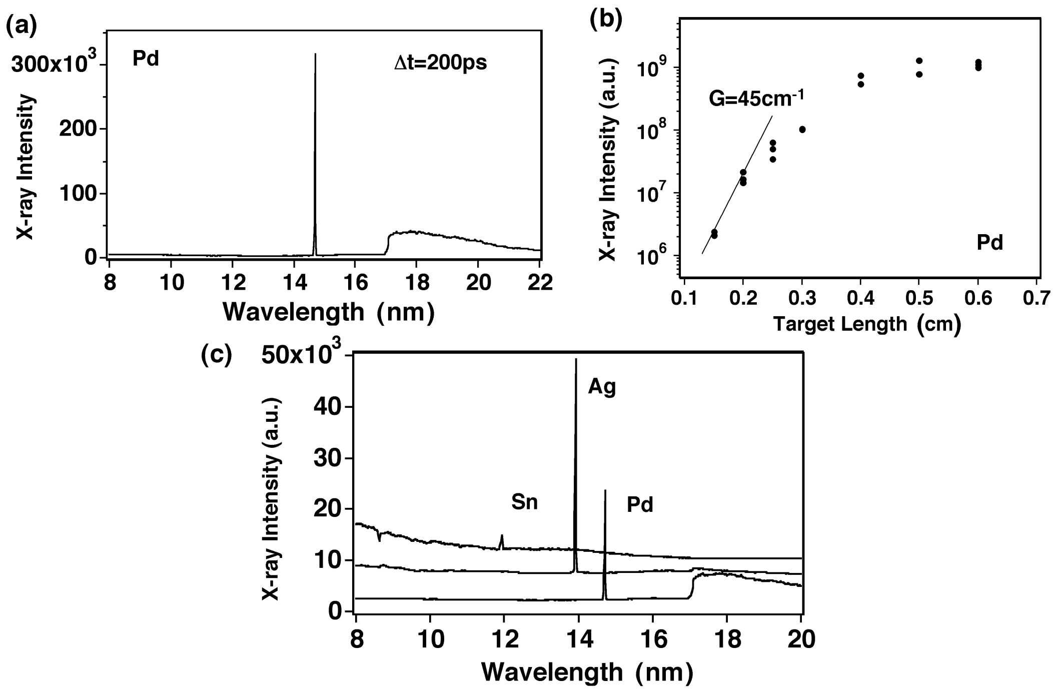


Fig. 7 (a) Spectrum, filtered with 200 nm Al, from an irradiated 0.6 cm Pd slab target showing strong emission from the 14.7 nm Ni-like Pd laser line. (b) Intensity vs length scan for Pd slab targets. Time delay of $\Delta t$ = 200 ps between the two pulses gives highest x-ray laser output. Small signal gain is determined to be 45 $cm^{-1}$. (c) Several single shot spectra from Pd, Ag, and Sn targets showing lasing at 14.7 nm, 13.9 nm and 11.9 nm wavelength, respectively.

300 nm Zr/100 nm polyimide.

## 4. Summary

In conclusion, our work in demonstrating the GRIP scheme was successful and has lead to new collaborations in this area. We predict the GRIP scheme will become the main technique for collisional pumping of mid-Z x-ray lasers operating above 10 nm. This has already been supported by the rapid adoption of this method by many groups new to the area of x-ray lasers. Secondly, the GRIP pumping scheme is ideal for generating high average power x-ray lasers in the 1 – 100 µW range. Some uses of the high average power capability have been demonstrated for microscopy at Colorado State University. Finally the GRIP scheme can be used for pumping a shorter wavelength x-ray laser below 10 nm. The obvious candidate would be to generate a “water-window” x-ray laser using a sub-Petawatt or Petawatt short pulse facility like Titan at LLNL or PHELIX at GSI, Darmstadt, Germany.

## Acknowledgments

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## LDRD Funding Allocation and External Funding over Duration of Project

FY03: Initial allocation $179k with plus up mid-year $219k
FY04: $186k
FY05: $121k
Total LDRD funding: $526k

Additional external funding of $85k was generated through the National Science Foundation funded Center for Biophotonics, Science and Technology. This was to investigate, by theoretical study by Dr. Shlyaptsev of UC Davis, the path to generating a shorter wavelength x-ray laser at intermediate wavelengths that would extend the grazing incidence pumping scheme to operate within or close to the carbon K-edge at 4.4 nm.

## Collaborations

In the course of the project, we expanded some of our external collaborations in order to investigate the plasma conditions of the grazing incidence pumping.

The group of Prof. Jorge Rocca at Colorado State University (CSU), specifically Jorge Filevich, was involved in conducting the x-ray laser interferometry of the Ni-like Pd plasma medium in order to determine the electron density conditions during the plasma-forming beam. This led to several publications relevant to the work (listed at the end of this report). In addition we collaborated with Prof. Jorge Rocca's group on the generation of the GRIP scheme at the high repetition rate laser facilities at CSU. The CSU had higher average power lasers suited to this pumping scheme and this led to further publications.

A visit to the Dr. Thomas Kuehl and the PHELIX Petawatt laser currently under construction at the GSI heavy ion beam facility at Darmstadt, Germany during September 2005 led to the discussion of GRIP short wavelength x-ray laser experiment. The PHELIX laser is based around a NOVA laser arm and new vacuum compressor with Dr. Thomas Kuehl, his co-workers and various European collaborators.

## Publication List (including Conference Proceedings) (13)

R. Keenan, J. Dunn, P.K. Patel, D.F. Price, R.F. Smith, and V.N. Shlyaptsev, "High Repetition Rate Grazing Incidence Pumped X-ray Lasers operating at 18.9 nm", Phys. Rev. Lett. **94**, 103901 (2005); UCRL-JRNL-204477.

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J. Dunn, J. Filevich, R. F. Smith, S. J. Moon, J. J. Rocca, R. Keenan, J. Nilsen, V. N. Shlyaptsev, J. R. Hunter, A. Ng, and M. C. Marconi, "Picosecond 14.7 nm interferometry of high Intensity laser-produced plasmas", Laser and Particle Beams **23**, 9 – 13 (2005); UCRL-JRNL-207241.

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R. Smith, J. Dunn, J. Filevich, S. Moon, J. Nilsen, R. Keenan, V.N. Shlyaptsev, J.J. Rocca, J.R. Hunter, R. Shepherd, R. Booth, M.C. Marconi, "Improved Energy Coupling into the Gain Region of the Ni-like Pd Transient Collisional X-ray Laser", Proceedings of the *9th International Conference on X-ray Lasers*, Beijing, China, May 23-28, 2004, *in press*; UCRL-PROC-207450.

R. Keenan, J. Dunn, V.N. Shlyaptsev, R.F. Smith, P.K. Patel, and D.F. Price, "Efficient Pumping Schemes for High Average Brightness Collisional X-ray Lasers", *Soft X-ray Lasers and Applications V*, ed. E.E. Fill and S. Suckewer, SPIE Int. Soc. Opt. Eng. Proc. **5197**, 213 (2003).

V.N. Shlyaptsev, J. Dunn, S.J. Moon, R.F. Smith, R. Keenan, J. Nilsen, K.B. Fournier, J. Kuba, A.L. Osterheld, J.J. Rocca, B. Luther, Y. Wang, and M. Marconi, "Numerical Studies of Transient and Capillary X-ray Lasers and Their Applications", *Soft X-ray Lasers and Applications V*, ed. E.E. Fill and

S. Suckewer, SPIE Int. Soc. Opt. Eng. Proc. **5197**, 221 (2003).

V.N. Shlyaptsev, "Modeling of Grazing Incidence Pumping Scheme", Int. Rep., University of California, Lawrence Livermore National Laboratory, UCRL-SR-201464 (2003).

## Invited Talks List (9)

J. Dunn, "US Activities in the Development of Plasma-based X-ray Lasers", European LaserNet Workshop on *Plasma-based X-ray Lasers*, organizers B. Rus and A. Klisnick, Prague, Czech Republic, Sept. 1 - 2, 2005; UCRL-CONF-216149.

J. Dunn, R. Keenan, S. Moon, A. Nelson, J. Nilsen, R. Shepherd, R. Smith, F. Weber, H. Fiedorowicz, A. Bartnik, J. Rocca, J. Filevich, V.N. Shlyaptsev, P. Zeitoun, "X-ray Laser Source Development and Applications at Lawrence Livermore National Laboratory" presented at Inst. for Optoelectronics, Military Univ. of Technology, Warsaw, Poland 6 Sept. 2005 UCRL-PRES-216144.

J. Dunn, R. Keenan, S. Moon, A. Nelson, J. Nilsen, R. Shepherd, R. Smith, J. Rocca, J. Filevich, V.N. Shlyaptsev, P. Zeitoun, "Characterization and Applications of Laser-Driven X-ray Lasers", *Atomic Spectroscopy in High Fields Workshop*, Piaski, Poland 6 - 11 Sept. 2005; UCRL-CONF-216064.

J. Dunn, R. Keenan, and V.N. Shlyaptsev, "Grazing Incidence Pumping For High Efficiency X-ray Lasers", Soft X-ray Lasers and Applications VI, SPIE International Symposium on Optics and Photonics, San Diego, CA, 31 July - 4 August, 2005; UCRL-ABS-213719.

R. Keenan, J. Dunn, P.K. Patel, D.F. Price, R.F. Smith, and V.N. Shlyaptsev, "Grazing Incidence Pumped (GRIP) X-ray Lasers at LLNL", LLNL Post-Doctoral Symposium, December 14, 2004, University of California, Lawrence Livermore National Laboratory; UCRL-BOOK-208545.

J. Dunn, R. Keenan, A.J. Nelson, R.F. Smith, J. Nilsen, S.J. Moon, A. Ng, P.K. Patel, D.F. Price, T. Van Buuren, J. Filevich, J.J. Rocca, M.C. Marconi, and V.N. Shlyaptsev, "Recent Developments in Tabletop X-ray Laser Sources and Applications", 28th European Conference on Laser Interaction with Matter, Rome, Italy, September 6-10, 2004; UCRL-ABS-213719.

J. Dunn, R. Keenan, V.N. Shlyaptsev, R.F. Smith, P.K. Patel, and D.F. Price, "Grazing Incidence Pumping for Efficient X-ray Lasers", 9th International Conference on X-ray Lasers, Beijing, China, May 23-28, 2004; UCRL-ABS-204478.

R. Smith, J. Dunn, J. Filevich, S. Moon, J. Nilsen, R. Keenan, V.N. Shlyaptsev, J.J. Rocca, J.R. Hunter, R. Shepherd, R. Booth, M.C. Marconi, "2-D Interferometric, Near-field and Temporal characterization of the Transient Collisional X-ray Laser", 9th International Conference on X-ray Lasers, Beijing, China, May 23-28, 2004.

V. N. Shlyaptsev, J. Dunn R. Keenan *et al*, "Pumping Efficiency of transverse, longitudinal and grazing incidence schemes in laser produced and capillary discharge plasmas", 9th International Conference on X-ray Lasers, Beijing, China, May 23-28, 2004.

## Conference Presentations

R. Keenan, J. Dunn, P.K. Patel, D.F. Price, R.F. Smith, and V.N. Shlyaptsev "A High Efficiency Grazing Incidence Pumped X-ray Laser Operating at 10 Hz", LLNL Post-Doctoral Symposium, January 8, 2004, University of California, Lawrence Livermore National Laboratory, UCRL-POST-201276 (2004).

R. Keenan, J. Dunn, V.N. Shlyaptsev, R.F. Smith, P.K. Patel, and D.F. Price, "A 10 Hz Grazing Incidence pumped Ni-like Mo laser at 18.9 nm with 150 mJ pump energy", 9th International Conference on X-ray Lasers, Beijing, China, May 23-28, 2004; UCRL-ABS-204476.

R. Keenan, J. Dunn, V.N. Shlyaptsev, R.F. Smith, P.K. Patel, and D.F. Price, "Efficient Pumping Schemes for High Average Brightness Collisional X-ray Lasers", SPIE conference on *Soft X-ray Lasers and Applications V*, San Diego, CA Aug 6 - 7, 2003.

V.N. Shlyaptsev, J. Dunn, S.J. Moon, R.F. Smith, R. Keenan, J. Nilsen, K.B. Fournier, J. Kuba, A.L. Osterheld, J.J. Rocca, B. Luther, Y. Wang, and M. Marconi, "Numerical Studies of Transient and Capillary X-ray Lasers and Their Applications", SPIE conference on *Soft X-ray Lasers and Applications V*, San Diego, CA August 6 - 7, 2003.

Two additional poster presentations at the UC Davis Center for Biophotonics Science and Technology Annual retreat in July 2004 and 2005.